SUPPLEMENTAL MATERIAL

Text A1.

To evaluate the degree of support for interactive range-limit theory (iRLT) – an extension of range-limit theory (RLT) – and the extent to which biotic interactions varied by trophic level, we performed a literature review of terrestrial and arboreal mammals from North America with an initial criterion of 30 genera from 10 families, representing 5 orders (Table S1). We chose genera as the finest taxonomic resolution because most studies included the genus name of a focal species, rather than higher taxonomic levels. We opportunistically included genera when our search results provided studies that were within the focus of the review, yet not included on the original list. We noted the occurrence of these genera in the text and tables below.

We used 2 approaches to search for literature. We used a systematic approach conducting 5 unique searches on the Web of Science (WOS) and 2 on Google Scholar (GS), using the same search terms for those that overlapped (Table S2). Note that GS has a 256-character limit and only provides the first 1,000 results so we performed multiple GS searches for each unique search. We also took a non-systematic approach, searching for literature on taxa that we were more familiar with, including our own studies. This approach allowed us to increase our sample size and find local and regional studies that evaluated causal mechanisms influencing fitness along range edges. It also provided older literature that may have used terminology different than the search terms we used. We distinguished between systematic and non-systematic searches and summarized each.

From 23-31 January 2019, we performed two different searches based on the aforementioned criteria. Our first and second WOS searches provided a total of 63 and 11 results, respectively (Table S2). Our first and second GS searches provided a total of 6,620 and 1,758 results, respectively (Table S2). Our third – fifth searches from WOS provided a total of 358, 9, and 65 results, respectively (Table S2). From this list, we searched through each result, first examining the title and abstract to determine if the study met our criteria. For our first search, we obtained 33 and 112 relevant papers from WOS and GS, respectively. Our second search provided 3 and 34 relevant papers from WOS and GS, respectively (Table S2). We found 19, 4, and 22 relevant papers from our remaining WOS searches (Table S2). Note that GS typically provides more results as it does not filter out gray literature. Our combined search (taking overlap among and within searches and search engines into account) resulted in a total of 97 papers. We then split multi-species papers or those that evaluated dynamics along multiple edges (e.g., upper and lower elevation edges) into separate entries in order to evaluate each species separately. Combined, our systematic review provided a total of 135 entries that met our criteria. Our non-systematic review yielded 131 unique papers (154 after splitting multi-species papers into separate entries); of these, 33 of the papers overlapped with the systematic review. Accounting for multi-species studies, we narrowed our review to 342 entries from 257 unique papers.

To narrow our review further, we searched through each of the 342 papers and tallied multiple items, including the latitudinal/altitudinal edge (High-latitude/altitude, Low-latitude/altitude), ecological variable measured in the study (e.g., Distribution, Survival), abiotic factor (e.g., Temperature), biotic factor (e.g., Habitat), abiotic and biotic responses (Positive, Negative, Neutral, Inferred, NA), biotic interaction (Yes, Inferred, NA), biotic interaction type (e.g., Competition, Predation), whether or not the study was conducted beyond the limit of the species range (Yes/No), and the type of study (Observational, Experimental, Descriptive). Note, we recorded positive or negative abiotic or biotic responses if the study indicated a statistically significant effect; a neutral assignment indicated no statistical relationship. We also recorded if the study evaluated static or dynamic range edge dynamics, and if the latter we recorded if the population(s) expanded, contracted, or remained stable. Finally, we assigned the scale (Local, Regional, Geographic) of each study based on the following criteria. We characterized studies as "Local" if they only sampled one population or a subset of a population; these studies usually used methods such as radio-telemetry that are typically limited to local extents. We labeled studies as "Regional" if they sampled >1 population and/or used survey methods that allow for broad spatial sampling (e.g., camera surveys). Lastly, we characterized studies as "Geographical" if the authors explicitly noted that they surveyed the entire geographic range of a species; these studies often used museum or harvest data. To increase the accuracy of our classifications, we paid special attention to the text of each article to determine whether a study was "Local", "Regional", or "Geographic" and used these clues to further refine the scale of the study. Although, these definitions of scale may be somewhat arbitrary, these criteria allowed us to filter our results to ensure we were including studies that were appropriate for evaluating iRLT (i.e., we were not biasing results based on local patterns). We omitted any papers that were reviews (unless they also included a single-species case study) or not conducted along or near range limits. These final criteria reduced our list from 257 to 217 unique papers (342 to 290 entries, including papers with multi-species). These papers are listed below in the reference section. Our search from the systematic and non-systematic reviews increased the number of families and genera to 15 and 31, respectively, and provided a total of 52 species. We used these remaining studies to evaluate iRLT and the extent to which biotic interactions varied by trophic levels.

To evaluate support for iRLT, we selected studies that evaluated regional and geographic scale distribution (i.e., first and second order resource selection; sensu Johnson, 1980) or abundance; studies of abundance were rare and only represent a small proportion of our review. This reduced our list from 290 to 216 entries and excluded many of the local studies which evaluated measurements of fitness (e.g., survival); the latter entries were used to discuss the possible mechanisms limiting populations along range edges and evaluate the extent to which biotic interactions varied by trophic level. We filtered the distribution studies based on 2 criteria. Our primary method for evaluating iRLT included only those studies that evaluated abiotic *and* biotic factors (138 entries). Our secondary method only included studies that evaluated abiotic *or* biotic factors (78 entries). We evaluated evidence for iRLT based on 2 criteria: We expected that the original predictions of RLT would be evident (negative abiotic factors along high-latitude/altitude limits and negative biotic interactions along low-latitude/altitude limits), except for two caveats; studies of populations along high-latitude/altitude limits would also document strong and positive biotic effects, whereas those along low-latitude/altitude limits would detect strong and positive associations with abiotic factors. Accordingly, we tallied the number of positive and negative abiotic factors and biotic factors along each edge and provide results in Table 2 of the manuscript, which includes 138 studies that evaluated both abiotic and biotic factors, and those that only include abiotic or biotic factors (n = 78) are listed in Table S4. For distribution-level studies we also tallied the number of studies that documented range shifts along high-latitude/altitude or low-latitude/altitude limits. We summarized the results in Table S5.

To evaluate if there were any potential biases from our non-systematic search, we conducted Fisher-exact tests of independence to 1) determine if the frequency of positive, neutral, or negative abiotic and biotic factors along range edges (High/Low) differed between search types, and 2) the frequency of biotic interactions differed between search types. We set $\alpha = 0.05$ and considered our systematic review to be biased if $P < 0.05$. All analyses were performed using the ‘fisher.test’ function in R (R Development Core Team, 2018). We did not find any statistical differences between search types for the frequency of positive, neutral, and negative 1) abiotic factors along high-latitude/altitude limits ($P = 0.636$), 2) abiotic factors along low-latitude/altitude limits ($P = 0.306$), and 3) biotic factors along low-latitude/altitude limits ($P = 0.332$). Our non-systematic review found a higher frequency of studies that reported positive biotic factors along high-latitude/altitude limits ($P = 0.044$). However, the systematic review also indicated a higher number of positive, rather than negative, biotic factors along upper range limits. Finally, we did not detect any differences between search types for the frequency of biotic interactions along high- and low-latitude/altitude limits ($P = 1$). Overall, we considered the additional entries provided by our non-systematic review to be complementary, with only a slight positive bias towards positive biotic factors along high latitude/altitude limits. Summaries of data used for these tests are listed in Table S6 and Table S7.

We used a similar approach to evaluate the extent to which biotic interactions varied by trophic level. Of the 290 entries, 96 evaluated biotic interactions. We compared the frequency of biotic interaction types (competition and predation/parasitism) between carnivores and herbivores. We found a higher frequency of competitive interactions for carnivores compared to herbivores ($P < 0.0001$); the latter were more influenced by predation and parasitism. To evaluate support for the RLT prediction of negative biotic interactions limiting low-latitude/altitude populations, we compared the frequency of biotic interactions between high-latitude/altitude and low-latitude/altitude limits for carnivores and herbivores. There were no significant differences between trophic levels ($P = 0.456$); negative biotic interactions occurred more frequently for both along lower limits. Tabular summaries of these analyses are provided in Table 3 of the manuscript.

Table S1. List of the taxonomic orders, families, and genera included in the systematic review.

Order	**Family**	**Genera**
Carnivora	Felidae	Lynx
		Puma*
	Mustelidae	Pekania
		Martes
		Mustela
		Gulo
	Canidae	Canis
		Vulpes
		Urocyon*
	Ursidae	Ursus
	Procyonidae	Procyon**
Didelphimorphia	Didelphidae	Didelphis
Artiodactyla	Cervidae	Alces
		Odocoileus
		Cervus
		Rangifer
	Bovidae	Ovis**
Lagomorpha	Leporidae	Lepus
		Sylvilagus
	Ochotonidae	Ochotona**
Rodentia	Sciuridae	Sciurus
		Tamiasciurus*
		Glaucomys
		Tamias
		Marmota*
		Urocitellus
		Poliocitellus**
		Cynomys**
	Erethizontidae	Erethizon
	Cricetidae	Peromyscus
		Microtus
		Myodes
		Lemmus*
		Synaptomys*
		Dicrostonyx
	Dipodidae	Napaeozapus**
	Castoridae	Castor**

*No results returned for these genera.
**New genera included in review from systematic search.

Table S2. Total number of results (T) and relevant papers (R) from systematic searches performed from 23–31 January 2019 using Google Scholar (GS) and Web of Science (WOS).

Search Engine*	Search	Search Date	Search String	T	R
WOS	First	1/25/2019	TS=(“Range Limit*” OR “Range Edge*”) AND TS=(Lynx OR Puma OR Pekania OR Martes OR Gulo OR Canis OR Vulpes OR Didelphis OR Alces OR Odocoileus OR Cervus OR Rangifer OR Lepus OR Sylvilagus OR Sciurus OR Tamiasciurus OR Glaucomys OR Urocitellus OR Erethizon OR Peromyscus OR Microtus OR Myodes OR Lemmus OR Mustela OR Urocyon OR Ursus OR Tamias OR Marmota OR Synaptomys OR Dicrostonyx)	63	33
GS	First	1/23/19 - 1/24/19	“Range Limit” OR “Range Edge” OR “Range Limits” OR “Range Edges” Lynx OR Puma OR Pekania OR Martes OR Gulo OR Canis OR Vulpes OR Didelphis OR Alces OR Odocoileus OR Cervus OR Rangifer OR Lepus OR Sylvilagus OR Sciurus OR Tamiasciurus OR Glaucomys OR Urocitellus OR Erethizon OR Peromyscus OR Microtus OR Myodes OR Lemmus OR Mustela OR Urocyon OR Ursus OR Tamias OR Marmota OR Synaptomys OR Dicrostonyx	6,620	131
WOS	Second	1/25/2019	TS=(Abiotic AND Biotic AND Distribution) AND TS=(“Range Limit*” OR “Range Edge*”) AND TS=(Lynx OR Puma OR Pekania OR Martes OR Gulo OR Canis OR Vulpes OR Didelphis OR Alces OR Odocoileus OR Cervus OR Rangifer OR Lepus OR Sylvilagus OR Sciurus OR Tamiasciurus OR Glaucomys OR Urocitellus OR Erethizon OR Peromyscus OR Microtus OR Myodes OR Lemmus OR Mustela OR Urocyon OR Ursus OR Tamias OR Marmota OR Synaptomys OR Dicrostonyx)	11	2
GS	Second	1/24/2019	Abiotic Biotic Distribution “Range Limit” OR “Range Edge” OR “Range Limits” OR “Range Edges” Lynx OR Puma OR Pekania OR Martes OR Gulo OR Canis OR Vulpes OR Didelphis OR Alces OR Odocoileus OR Cervus OR Rangifer OR Lepus OR Sylvilagus OR Sciurus OR Tamiasciurus OR Glaucomys OR Urocitellus OR Erethizon OR Peromyscus OR Microtus OR Myodes OR Lemmus OR Mustela OR Urocyon OR Ursus OR Tamias OR Marmota OR Synaptomys OR Dicrostonyx	1758	40

*GS has a 256-character limit, so we performed 3 searches for each search criteria splitting the names of genera to accommodate this limit and to ensure consistency with searches performed on WOS.

Table S2. Total number of results (T) and relevant papers (R) from systematic searches performed from 23–31 January 2019 using Google Scholar (GS) and Web of Science (WOS).

Search Engine*	Search	Search Date	Search String	T	R
WOS	Third	1/31/2019	TS=(Distribution*) AND TS=(Abiotic OR Biotic) AND TS=(Lynx OR Bobcat OR Puma OR Cougar OR "Mountain lion*" OR Pekania OR Fisher OR Martes OR Marten* OR Gulo OR Wolverine* OR Canis OR Coyote* OR Wolf* OR Vulpes OR Fox* OR Didelphis OR Opossum* OR Alces OR Moose OR Odocoileus OR Deer OR Cervus OR Elk OR Rangifer OR Caribou OR Reindeer OR Lepus OR Hare* Or Sylvilagus OR Rabbit* OR Sciurus OR Squirrel* OR Tamiasciurus OR Glaucomys OR "Flying squirrel*" OR Urocitellus "Ground squirrel*" OR Erethizon OR Porcupine* OR Peromyscus OR Mouse OR Mice OR Microtus OR Vole* OR Myodes "Red backed vole*" OR Lemmus OR Lemming* OR Mustela OR Weasel* OR Urocyon OR "Gray fox*" OR "Grey fox*" OR Ursus OR Bear* OR Tamias OR chipmunk* OR Marmota OR Marmot* OR Groundhog* OR Synaptomys OR "Bog lemming*" OR Dicrostonyx OR "Collared lemming*")	358	19
WOS	Fourth	1/31/2019	TS=(Distribution*) AND TS=(Abiotic OR Biotic) AND TS=("Range Limit*" OR "Range Edge*") AND TS=(Lynx OR Bobcat OR Puma OR Cougar OR "Mountain lion*" OR Pekania OR Fisher OR Martes OR Marten* OR Gulo OR Wolverine* OR Canis OR Coyote* OR Wolf* OR Vulpes OR Fox* OR Didelphis OR Opossum* OR Alces OR Moose OR Odocoileus OR Deer OR Cervus OR Elk OR Rangifer OR Caribou OR Reindeer OR Lepus OR Hare* Or Sylvilagus OR Rabbit* OR Sciurus OR Squirrel* OR Tamiasciurus OR Glaucomys OR "Flying squirrel*" OR Urocitellus "Ground squirrel*" OR Erethizon OR Porcupine* OR Peromyscus OR Mouse OR Mice OR Microtus OR Vole* OR Myodes "Red backed vole*" OR Lemmus OR Lemming* OR Mustela OR Weasel* OR Urocyon OR "Gray fox*" OR "Grey fox*" OR Ursus OR Bear* OR Tamias OR chipmunk* OR Marmota OR Marmot* OR Groundhog* OR Synaptomys OR "Bog lemming*" OR Dicrostonyx OR "Collared lemming*")	9	4
WOS	Fifth	1/31/2019	TS=(Distribution*) AND TS=("Range Limit*" OR "Range Edge*") AND TS=(Lynx OR Bobcat OR Puma OR Cougar OR "Mountain lion*" OR Pekania OR Fisher OR Martes OR Marten* OR Gulo OR Wolverine* OR Canis OR Coyote* OR Wolf* OR Vulpes OR Fox* OR Didelphis OR Opossum* OR Alces OR Moose OR Odocoileus OR Deer OR Cervus OR Elk OR Rangifer OR Caribou OR Reindeer OR Lepus OR Hare* Or Sylvilagus OR Rabbit* OR Sciurus OR Squirrel* OR Tamiasciurus OR Glaucomys OR "Flying squirrel*" OR Urocitellus "Ground squirrel*" OR Erethizon OR Porcupine* OR Peromyscus OR Mouse OR Mice OR Microtus OR Vole* OR Myodes "Red backed vole*" OR Lemmus OR Lemming* OR Mustela OR Weasel* OR Urocyon OR "Gray fox*" OR "Grey fox*" OR Ursus OR Bear* OR Tamias OR chipmunk* OR Marmota OR Marmot* OR Groundhog* OR Synaptomys OR "Bog lemming*" OR Dicrostonyx OR "Collared lemming*")	65	22

Table S3. Number of studies that found positive, negative, and neutral effects of abiotic and biotic factors on the distribution or abundance of North American mammalian carnivores and herbivores. **Note**: This table only includes studies that evaluated abiotic *and* biotic factors along range limits (n = 138).

Trophic Level	Range-limit	Factor	Positive	Negative	Neutral	Biotic interaction[a]	Total[b]
Carnivore	High	Abiotic	5	37	0		42
		Biotic	36	7	4	0	47
	Low	Abiotic	29	3	5		37
		Biotic	25	7	3	4	39
Herbivore	High	Abiotic	8	24	1		33
		Biotic	21	11	3	3	38
	Low	Abiotic	17	12	6		35
		Biotic	24	5	1	5	35

[a] Few studies coincidentally evaluated biotic interactions (e.g., competition, predation) at broader spatial scales.

[b] Note that some studies documented multiple abiotic or biotic factors, which occasionally had opposite signs. For example, if a study indicated that one abiotic variable had a positive effect, and another had a strong negative effect, we tallied these as separate records, which increased the total number of studies.

Table S4. Number of studies that found positive, negative, and neutral effects of abiotic and biotic factors and biotic interactions on the distribution or abundance of North American mammalian carnivores and herbivores. **Note**: This table only includes studies that evaluated abiotic *or* biotic factors along range limits (n = 78).

Trophic Level	**Range-limit**	**Factor**	**Positive**	**Negative**	**Neutral**	**Biotic interaction**[a]	**Total**[b]
Carnivore	High	Abiotic	0	7	0	0	7
		Biotic	11	2	0	0	13
	Low	Abiotic	2	1	0	0	3
		Biotic	10	3	0	0	13
Herbivore	High	Abiotic	2	4	0	0	6
		Biotic	10	0	0	0	10
	Low	Abiotic	8	1	0	0	9
		Biotic	12	6	0	0	18

[a] Relatively few studies coincidentally evaluated biotic interactions (e.g., competition, predation) at broader spatial scales.

[b]Note that some studies documented multiple abiotic or biotic factors, which occasionally had opposite signs. For example, if a study indicated that one abiotic variable had a positive effect, and another had a strong negative effect, we tallied these as separate records, which increased the total number of studies.

Table S5. Number of studies reporting range contraction, expansion, and stability along high-latitude/altitude and low-latitude/altitude limits.

Range-limit	Contraction	Expansion	Stability
High	4	13	1
Low	14	5	2

Table S6. Number of studies from our systematic and non-systematic review, and those that overlapped, which reported positive, neutral, or negative abiotic and biotic factors along range limits.

Review Type	Factor	Range-limit	Positive	Neutral	Negative
Systematic review	Abiotic	High	3	1	17
		Low	16	7	7
Non-systematic review		High	4	0	30
		Low	19	3	3
Overlap		High	5	0	13
		Low	10	0	5
Systematic review	Biotic	High	13	4	9
		Low	23	1	8
Non-systematic review		High	28	3	4
		Low	17	3	3
Overlap		High	16	0	5
		Low	8	0	1

Table S7. Number of studies from our systematic and non-systematic review, and those that overlapped, which reported biotic interactions along range limits.

Range-limit	Systematic review	Overlap	Non-systematic review
Low	21	13	28
High	12	2	16

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